Surface Wave Processes on the Continental Shelf and Beach

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Award Numbers: N0001407WR20142, N0001407WR20227, N00014-07-1-0365, N00014-07-1-0402
http://www.oc.nps.navy.mil/wavelab/

LONG-TERM GOALS

Wind waves and swell dominate the hydrodynamic and sediment transport processes on many continental shelves and beaches, affect underwater acoustics, and play an important role in remote sensing applications. Wave prediction in coastal environments is a challenging task because waves are affected by many processes, including scattering by seafloor topography, strong nonlinear interactions, wave breaking, and friction in the bottom boundary layer. Several of these processes are poorly understood and existing wave prediction models rely on parameterizations and empirical validation to represent them. The long term goals of this research are to obtain a better understanding of the physical processes that affect ocean surface waves in the coastal environment and develop accurate wave prediction models.

OBJECTIVES

- Predict the nonlinear shoaling transformation of waves on beaches including the excitation of infragravity motions.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Surface Wave Processes on the Continental Shelf and Beach**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Department of Oceanography,Monterey,CA,93943**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Observe the seafloor damping effects on ocean surface waves in sandy and muddy coastal environments.

- Model the effects of a fluid-mud layer on wind wave evolution.

- Improve the representation of source terms in operational wave prediction models.

- Advance deterministic and stochastic modeling capability for nonlinear wave evolution over complex seafloor topography.

APPROACH

We use a combination of theory, numerical models, and field experiments to investigate the physical processes that affect ocean surface waves on continental shelves and beaches. The transformation of wave spectra is predicted with models that include the effects of refraction, scattering by wave-wave and wave-bottom interactions, and parameterizations of bottom friction, and wave breaking. Extensive field data sets were collected in ONR experiments off North Carolina (DUCK94, SandyDuck, SHOWEX), California (NCEX), and the Florida Gulf coast (SAX04/Ripples) to test these models in a range of coastal environments. New experiments are underway on the sandy Martha's Vineyard shelf and the muddy Louisiana shelf. Analysis techniques applied to the measurements include various inverse methods to extract directional and wavenumber properties from array cross-spectra, higher-order spectral analysis to detect nonlinear coupling, as well as standard statistical methods to determine empirical relationships between observed variables. The modeling efforts include deterministic and stochastic models that incorporate quadratic and cubic nonlinearity and wide angle diffraction effects, suitable for application to energetic wave environments with complex seafloor topography.

WORK COMPLETED

During FY07 we continued to contribute to the analysis of observations collected in the Nearshore Canyon Experiment (NCEX) which took place during the fall of 2003 near the La Jolla and Scripps submarine canyons on the southern California coast. In collaboration with Jim Thomson, Steve Elgar, and Britt Raubenheimer at WHOI and Rudy Magne and Fabrice Ardhuin at the French Naval Oceanographic Center, Brest, we studied the effects of complex bathymetry on the nearshore wave field.

Jim Thomson investigated the generation and propagation of infragravity waves. His work showed that infragravity waves nonlinearly excited in the surf zone are strongly affected by refraction and reflections over the canyons in agreement with geometrical optics (Thomson et al., 2006, 2007).

Rudy Magne examined the transformation of swell over a submarine canyon using a coupled-mode theory for the full linear potential flow problem including evanescent modes (Athanassoulis and Belibassakis, 1999). Comparisons of model results and observations from the NCEX experiment show that refractive trapping of waves by the offshore canyon rim effectively blocks the arrival of long period swell on the adjacent beach.

During FY07 we also contributed to analyses of the SandyDuck and SHOWEX data sets. Fabrice Ardhuin compared observations of fetch-limited wind waves on the continental shelf to predictions of third-generation wave prediction models including full computations of the Boltzmann integral of nonlinear wave-wave interactions (Ardhuin et al., 2007). These comparisons highlight some deficiencies of wave growth and dissipation parameterizations in mixed swell-sea conditions.

The Martha's Vineyard Experiment, focused on seafloor ripples excited by the orbital motion of ocean surface waves, is currently in progress. In late August we deployed an array of wave measuring instruments to observe in detail the wave evolution across the inner continental shelf (Figure 1). The measurements will be used to test new models for nonlinear wave evolution in variable depth (discussed below) and provide the hydrodynamic forcing conditions for collaborative studies of the coupled wave-morphology dynamics. The array spans a 5 km distance from 8- to 24-m depth, including the dynamic inner shelf region. Two Datawell Directional Waverider buoys were deployed along the deeper part of the transect in 24 and 20 m depth. In the middle of the transect an 8-element coherent array of bottom pressure transducers was deployed in 18-15 m depth to provide detailed measurements of the two-dimensional wave group structure. At the shallow end of the transect six bottom tripods with an acoustic Doppler velocimeter and an acoustic Doppler profiler (each also containing a pressure transducer) provide near-bed velocity measurements and surface wave directional spectra. The tripods were deployed along the 10- and 12-m isobaths in fine and coarse sediment patches to study the effect of the heterogeneous sediment environment on the wave-seafloor interactions. The sensor locations were coordinated with the deployment of other tripods (small black squares) by Peter Traykovski (WHOI), Alex Hay (Dalhousie Univ.), and Chris Sherwood (USGS) that are equipped with a variety of seafloor mapping instruments in addition to surface wave sensors. The combined array will provide a unique, densely sampled surface wave data set for testing models described below. In addition to the fixed arrays, the Sherwood and Traykovski groups are also collecting extensive side-scan sonar surveys of the seafloor morphology changes in the instrumented area.

Preparations are currently underway for the Louisiana Experiment where we plan to observe wave evolution over a muddy seafloor. A new bottom tripod was developed for this experiment (Figure 2) with an elevated base and a detachable (through acoustic releases) instrument platform. These tripods are also deployed in the ongoing Martha's Vineyard Experiment, where they performed well so far.

RESULTS

To advance modeling capability of nonlinear wave evolution on the continental shelf in the presence of heterogeneous bottom composition (e.g. mud or ripple patches), we developed both deterministic and stochastic models that are suitable for realistic random wave fields. The deterministic approach is well suited for the detailed modeling of nonlinear evolution on smaller scales (several kilometers), and serves as a benchmark for the development of stochastic models. The stochastic models are developed with the aim of application on larger scales, and future routine, operational use.

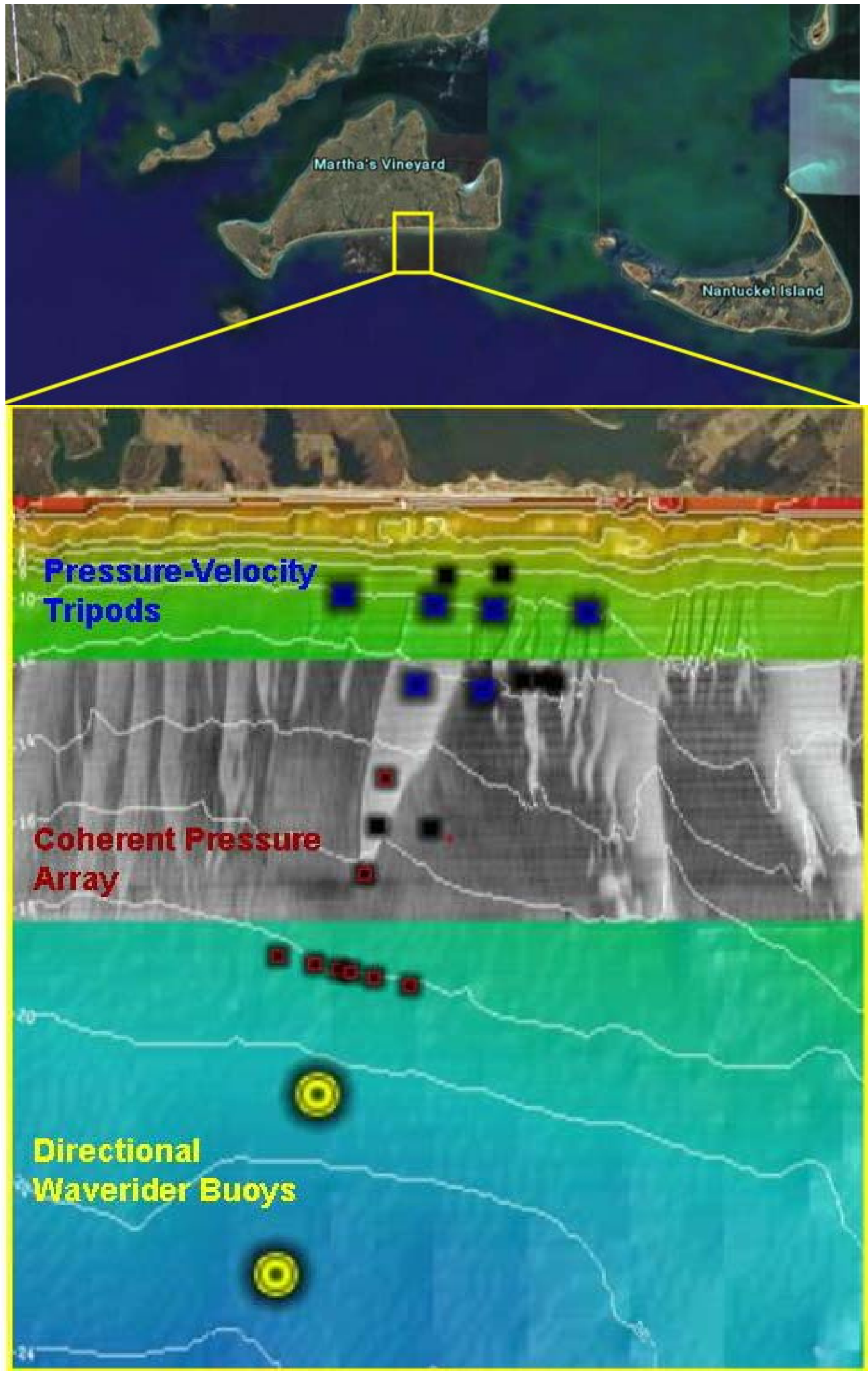

Figure 1. Array plan Martha's Vineyard Experiment. Detailed measurements of surface wave evolution across the inner shelf were collected during September and October of 2007. The array spans about 5 km from 24- to 8-m depth. The small black squares indicate tripods with seafloor mapping instruments deployed by other investigators. The overlay sidescan image (courtesy of Peter Traykovski) shows shore-normal ripple scour depressions.

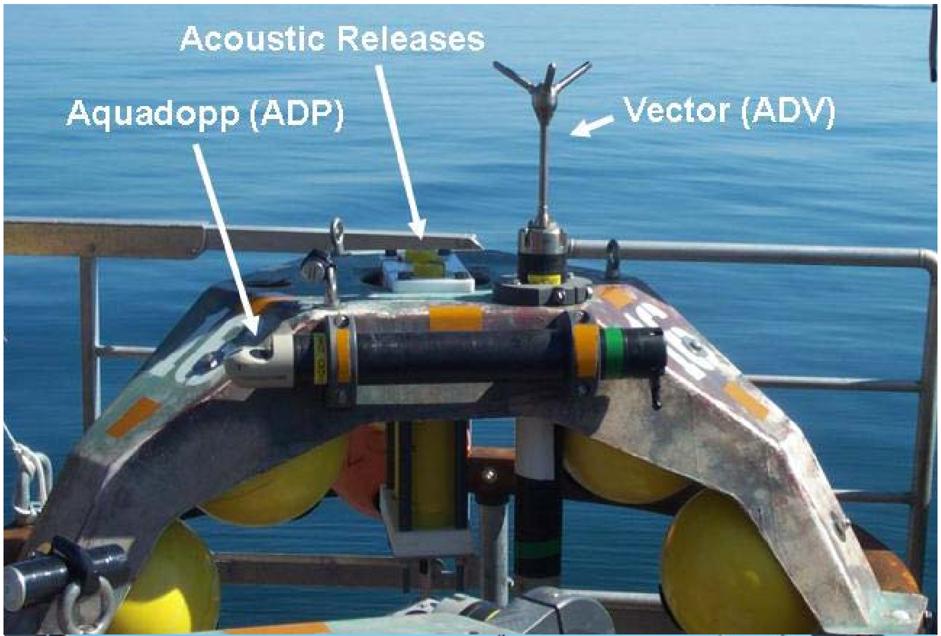

Figure 2. Pressure-velocity tripod. Top: detail of the instrument package including a Nortek Vector acoustic Doppler velocimeter, a Nortek Aquadopp acoustic Doppler profiler and dual acoustic releases. Bottom: deployment of the tripod off Martha's Vineyard. The height of the base frame is adjustable for future use in muddy environments.

Wave propagation in shallow areas with inhomogeneous bottom composition is affected by many processes including refraction, damping, nonlinearity and diffraction. Conventional stochastic models such as SWAN and WAVEWATCH III are based on an energy (or action) balance, which presumes the wave field's spectral constituents to be slowly varying and independent, implying a quasi-homogeneous, Gaussian sea state. This is effectively a geometrical optics approximation of the wave propagation and does not include diffraction. To account for diffraction in a statistical framework, a fundamentally different approach is needed.

Based on a forward-scattering approximation of the nonlinear mild-slope equation, we have developed a stochastic model that accounts for spatial inhomogeneity and non-Gaussian statistics [Janssen et al., in press]. Instead of assuming non-collinear wave components to be independent from the outset, we explicitly compute the cross-correlation between directional wave components induced by the heterogeneity of the bottom. This thus relaxes the assumption of spatial homogeneity of the waves. The computed cross-correlation matrix reproduces the complete (linear) statistics of the random wave field, including the coherent interference of crossing waves in the lee of topographic features such as shoals and islands.

To verify the diffraction capability of our new stochastic model, we consider narrow-band swell propagation through a breakwater gap (Figure 3), a severe test on the model's representation of diffraction effects. The agreement between the model prediction and the analytic solution confirms the wide-angle diffraction capability of the model.

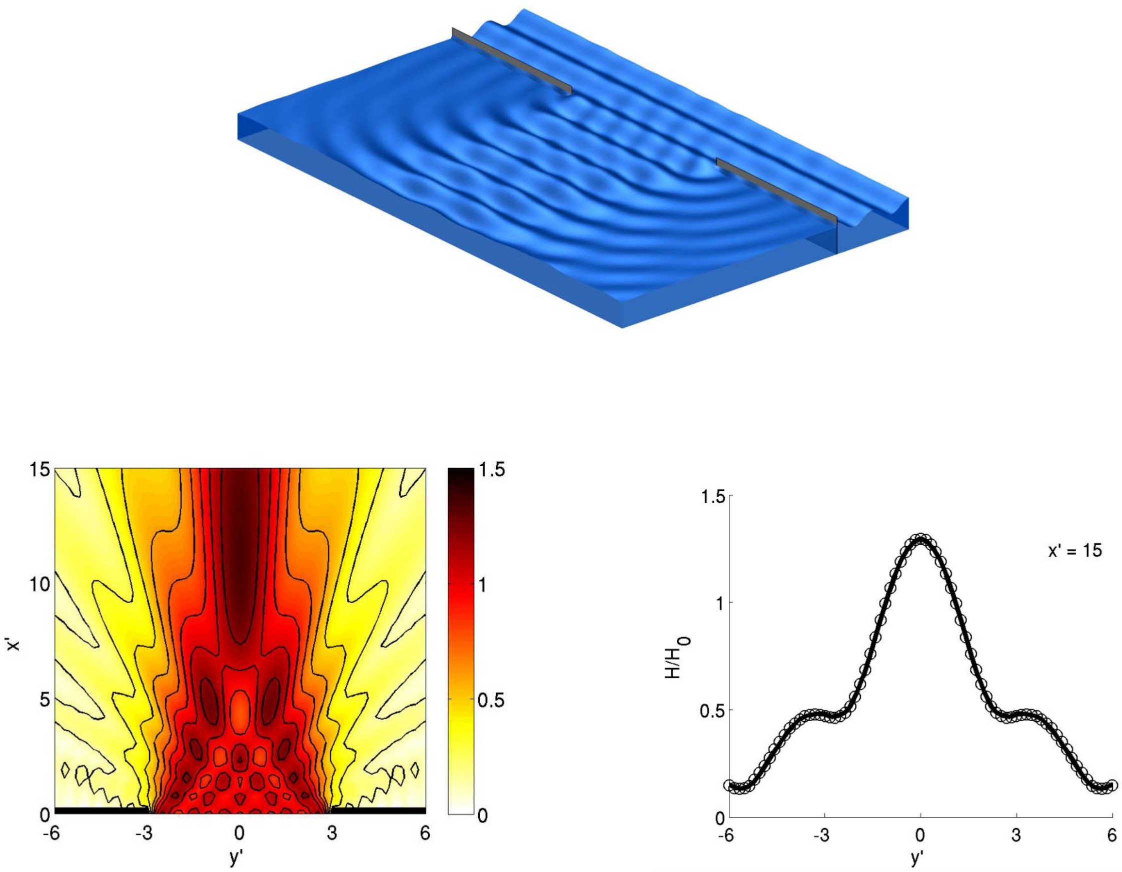

Figure 3. Verification stochastic model diffraction capabilities for wave field through gap [Janssen et al., in press]. Top panel: deterministic model prediction surface elevation behind the gap. Lower left panel: relative wave height prediction stochastic model. Lower right panel: lateral wave height variation 15 wavelengths behind the gap; comparison stochastic model prediction (solid line) to analytic solution (circles).

The representation of combined refraction-diffraction effects is tested through comparison to laboratory observations of narrow-band waves over a focusing shoal (Vincent & Briggs, 1989). The good agreement between model predictions and observations (Figure 4), in particular the lateral variations in wave height behind the shoal (lower right panel), confirms that the stochastic model has the capability to predict the coherent wide angle scattering effects induced by seafloor topography. Further, to enable modeling of shallow areas where nonlinearity and depth-induced wave breaking may be important, we account for quadratic nonlinearity and included a new wave breaking formulation to accommodate depth-induced wave breaking (Janssen and Battjes, 2007).

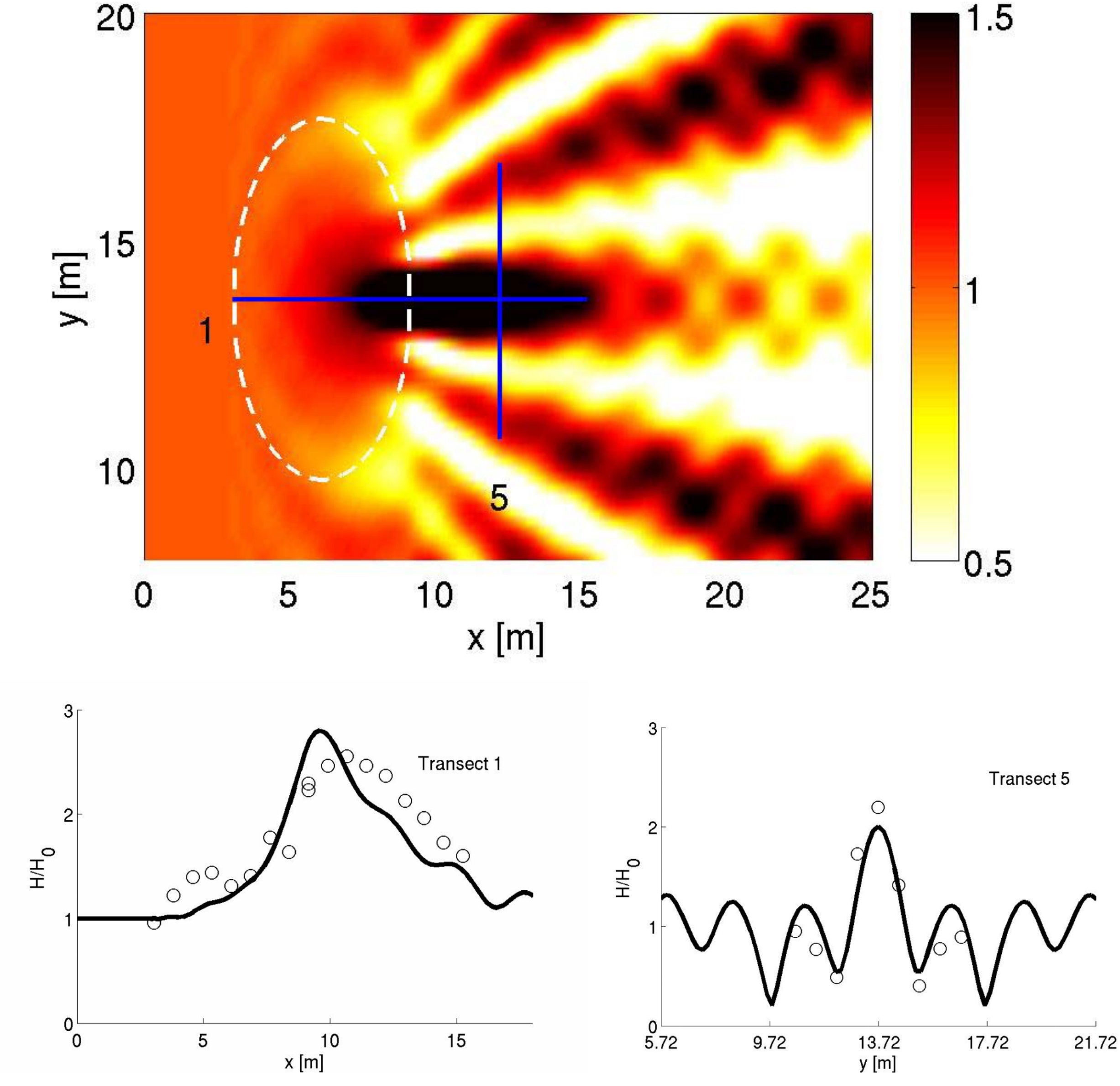

Figure 4. Monochromatic wave evolution over submerged shoal. Top panel: relative wave height computed with stochastic model [Janssen et al., in press]. Bottom panels: comparison predicted (solid line) and observed (circles, Vincent and Briggs, 1989) wave height along two transects (indicated in the top panel).

The development of this new stochastic model with wide-angle refraction-diffraction capability is a critical first step in developing an evolution model for surface wave statistics over complex and heterogeneous bottoms, including ripple scour depressions and mud deposits with complex rheology. Existing wave-mud direct-damping models can be readily included in this model.

We have implemented a wave-mud boundary layer damping model (Ng, 2000) into the nonlinear deterministic model to perform preliminary testing and verification (Figure 5). Unfortunately, detailed observations of wave damping rates are available only from laboratory experiments with uni-directional wave propagation (de Wit, 1995); comprehensive field observations of random multi-directional waves over natural mud deposits will be collected in the winter of 2008 on the Louisiana coast.

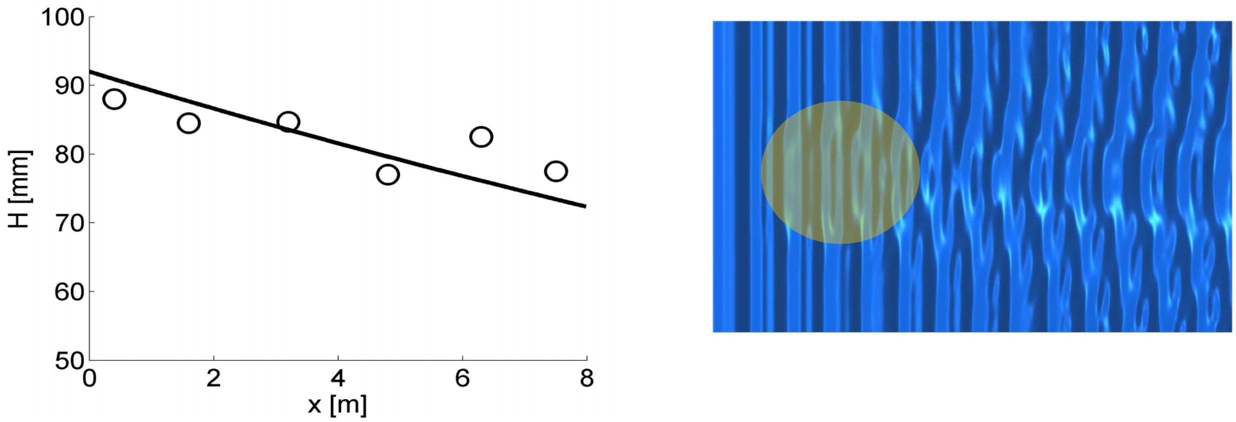

Figure 5. Wave evolution over mud. Left panel: comparison of model prediction (solid line) to laboratory observations (circles, de Wit, 1995). Right panel: model prediction of narrow-band waves impinging on a circular mud patch.

IMPACT/APPLICATIONS

Existing spectral wave prediction models do not account for diffraction effects in the vicinity of islands, inlets and abrupt bathymetry features and contain very crude parameterizations of seafloor damping effects. We are conducting new field experiments on sandy (Martha's Vineyard) and muddy (Louisiana) continental shelves that will provide the much needed comprehensive data sets for improving these parameterizations. We are also developing new deterministic and stochastic nonlinear wave evolution models that incorporate diffraction effects for more accurate predictions in complex coastal environments.

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